Recommendations for measuring whisker movements and locomotion in mice with sensory, motor and cognitive deficits.

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Highlights

1. Mice move their whiskers during tactile exploration.
2. We measure whisker movements and locomotion in 9 mouse strains.
3. Genotype, background strain, sex and source breeder affected whisker movements.
4. 8 of the 9 models showed differences in whisker movements, compared to controls.
5. We recommend a standardized protocol to measure whisker movements.

Recommendations for measuring whisker movements and locomotion in mice with sensory, motor and cognitive deficits.

Abstract

Background : Previous studies have measured whisker movements and locomotion to characterise mouse models of neurodegenerative disease. However, these studies have always been completed in isolation, and do not involve standardized procedures for comparisons across multiple mouse models and background strains.

New Method : We present a standard method for conducting whisker movement and locomotion studies, by carrying out qualitative scoring and quantitative measurement of whisker movements from high-speed video footage of mouse models of Amyotrophic Lateral Sclerosis, Huntington's disease, Parkinson's disease, Alzheimer's disease, Cerebellar Ataxia, Somatosensory Cortex Development and Ischemic stroke.

Results : Sex, background strain, source breeder and genotype all affected whisker movements. All mouse models, apart from Parkinson's disease, revealed differences in whisker movements during locomotion. R6/2 CAG250 Huntington's disease mice had the strongest behavioural phenotype. CKO and RIM-DKOSert mouse models have abnormal somatosensory cortex development and revealed significant changes in whisker movements during object exploration.

Comparison with Existing Method(s) : Our results have good agreement with past studies, which indicates the robustness and reliability of measuring whisking. We recommend that differences in whisker movements of mice with motor deficits can be captured in open field arenas, but that mice with impairments to sensory or cognitive functioning should also be filmed investigating objects. Scoring clips qualitatively before tracking will help to structure later analyses.

Conclusions: Studying whisker movements provides a quantitative measure of sensing, motor control and exploration. However, the effect of background strain, sex and age on whisker movements needs to be better understood.

Keywords: rodent, sensorimotor, barrel cortex, animal behaviour, neurodegeneration, disease models, transgenic, mouse models

Introduction

Studies on laboratory mice (*Mus musculus*) have contributed significantly to our understanding of human biology and health (Fox et al., 2006; Morse, 2007; Perlman, 2016), and mouse models are a powerful tool for research in biomedical science. This is mainly due to their genetic similarities to humans (Waterston et al., 2002), the ability to create transgenic, knock-out, and knock-in varieties, as well as the ease and relatively low expense of keeping and breeding them (Burns et al., 2015). However, the use of mice in biomedical research needs to take account of, and perhaps even advantage of, the differences between mice and humans (Perlman, 2016). Modern rodents and primates are thought to have diverged from a common ancestor around 85 million years ago (Springer and Murphy, 2007; Perlman, 2016). It is not, therefore, surprising that there are many genetic, physiological and behavioural differences between humans and mice. One of the striking features of mice is their prominent facial whiskers, or vibrissae. Whisker-brain connections are regularly studied by neuroscientists as a model system for sensory processing (Diamond et al., 2008; Kleinfeld et al., 2006). Indeed, the arrangement of whiskers on each side of a mouse's face are mimicked in physical topographic structures that can be seen throughout the brain in brainstem, thalamus and layer IV of somatosensory (Barrel) cortex (Waite, 1995; Petersen, 2007; Feldmeyer et al., 2013). Sensory processing of whisker signals in the cortex is likely to be involved in environmental exploration and object discrimination tasks (Kleinfeld et al., 2006; Grant et al., 2012; Hong et al., 2018).

As well as being an important tactile sensory system, whiskers also move. Indeed, mice can move their whiskers up to 25 times per second, in a process called whisking, which is amongst the fastest movements that mammals can make (Mitchinson et al., 2011). In addition to making simple, cyclic movements, mice can also alter the timing, spacing and positioning of their whiskers to maximise sensory information (Carvell and Simons, 1990; Grant et al., 2009; Mitchinson et al., 2007; 2011). For example, when contacting an object, rodents reliably and robustly reduce the spread of their whiskers, to bunch them up, increasing the number of whiskers that contact the object (Grant et al., 2009). Whisker movements also show contact-induced asymmetry, as the whiskers contralateral to the contact are positioned more forward to increase whisker contact, and the whiskers ipsilateral to the contact are positioned more backward to enable light touches against the surface (Mitchinson et al., 2007; 2011). Therefore, as well as a model of sensory processing, whiskers are also a good system for the study of motor control and exploratory behaviours. Moreover, the positioning and orienting of whiskers have been linked to the focussing of attention (Arkley et al., 2014; Huet et al., 2014; Mitchinson and Prescott, 2013; Towal and Hartmann, 2006), which suggests that the study of whisker movement might be used to measure cognitive function.

As whisker movements of mice are precisely controlled and can be accurately measured, they can provide quantitative behavioural measures of sensory processing, motor control, exploration and, possibly cognition. Indeed, changes in whisker movements have been observed in mouse models of motor disorders, including Amyotrophic Lateral Sclerosis (Grant et al., 2014) and Huntington's disease (Garland et al., 2018) during filming in a simple, open field arena. Moreover, whisker movement analysis revealed a behavioural phenotype in Huntington's disease R6/2 CAG250 and Hdh CAG250 knock-in mice at an earlier age than any other behavioural measure (Garland et al., 2018). Whisker movements are also altered in mouse models of anxiety (Grant et al., 2016) and Alzheimer's disease (Grant et al., 2018). Grant et al. (2018) utilised three tests for studying whisker movements in an Alzheimer's disease mouse model: object exploration, sequential object exploration and tunnel-running; however, only the object exploration task revealed significant differences in whisker movements in the transgenic (5xFAD) mice. Garland et al. (2018) compared whisker movements

among three different mouse models of Huntington's disease only in open field arenas. However, it is not clear whether experimental approaches should differ between mouse models of motor disorders, compared to disorders of sensory processing or cognitive functioning. Indeed, so far, studies of whisker movements have been conducted in isolation, and there have been no formal comparisons or recommendations for measuring whisker movements in different mouse models.

This paper will present a standard procedure for conducting whisker movement studies for the first time, by carrying out both qualitative scoring and quantitative measurement of high-speed video footage of whisker movements. We provide data on locomotion speeds and whisker movements in selected mouse models with motor disorders: Amyotrophic Lateral Sclerosis ($SOD1^{G93A}$), Huntington's disease (R/62 CAG250), Parkinson's disease (SNCA-OVX); Ischemic Stroke (MCAO, a sensory and motor model); Sensory alterations in somatosensory cortical map development: RIM-DKO Sert, $Robo3R^{3-5}$-cKO; Cerebellar Ataxia (Reeler B6c3Fe, which also have altered sensory cortical map development); and Cognitive functioning: Alzheimer's disease (3xTg-AD, 5xFAD). We measured whisker movements of mice in open-field environments for all mouse models, and investigated object exploration in a sub-set of models. After presenting our findings, we make recommendations for conducting standardized whisker movement studies in the future, in order to ensure robust comparisons between mouse models.

Methods

Mouse models

Whisker movement and locomotion speed data are presented from nine mouse models, including Amyotrophic Lateral Sclerosis ($SOD1^{G93A}$), Huntington's disease (R/62 CAG250), Parkinson's disease (SNCA-OVX), Stroke (distal middle cerebral artery occlusion (MCAO)), Cerebellar Ataxia (Reeler B6C3Fe), Cortical Development Disorders (RIM-DKO Sert, $Robo3R^{3-5}$-cKO) and Alzheimer's disease (3xTg-AD, 5xFAD). Data were collected from laboratories around the world (University of Sheffield, University of Cambridge, University of Oxford, University of Nottingham, University of Goettingen, INSERM, Dalhousie University, respectively). Details of genetic lines and controls can be found in the references in the first column of Table 1, husbandry information for the individual mice can be found in Appendix 1 and a description of the MCAO surgery can be found in Appendix 2. All animals had food and water *ad libitum* (apart from the MCAO mice, see Appendix 1 for more details).

Mice were removed from their home cage for 5-10 minutes, placed in a custom test apparatus for filming and then returned to their home cage. Each mouse was tested one to three times in total, but only once per day. All procedures were approved by ethical committees at the local institutions (University of Sheffield, University of Cambridge, University of Oxford, University of Nottingham, University of Goettingen, INSERM, University of Dalhousie, Manchester Metropolitan University), and carried out in accordance with regulations issued by the UK Home Office (at UK institutions), EU (at University of Goettingen and INSERM) and the Canadian Council of Animal Care (at University of Dalhousie).

Animals were selected when they were likely to show strong behavioural phenotypes, these were late stage in the disease process in transgenic mice and soon (2 weeks) after the middle cerebral artery occlusion (MCAO) surgery in stroke mice. In stroke, we also included a later date from surgery (1 month) when most deficits have usually recovered. Across labs, there were preferences for studying different genders, depending on ease of handling and disease progression. The genders tested can be seen in Table 1. Where possible, both males and females were tested, but this was

only possible for R6/2 CAG250 and Rim-DKOSert models, and their controls. All transgenic animals were compared to age-matched non-transgenic controls, apart from MCAO mice which were compared to sham controls (see Kuraoka et al., (2009) for more details), and SNCA-OVX mice which were compared to α-synuclein null (α-syn null) mice (see Janezic et al. (2013) for more details). The number of mice, and hence number of clips, varied between models due to the availiability of the animals. This may have impacted some of the results when sample sizes were smaller, such as for the RIM-DKO Sert, MCAO 2-week sham and 5xFAD mice. Sample sizes can be observed in Table 1.

Each mouse model was coded as to whether it would be likely to reveal sensory, motor or cognitive symptoms (for further evidence, refer to the discussion section). Considering these likely symptoms, the mice were tested to examine their whisker movements during locomotion (for all mouse models), and during object exploration (for Reeler B6C3Fe, RIM-DKOSert, Robo3R$^{3-5}$-cKO, 3xTg-AD, 5xFAD).

Table 1: Information about mouse models, controls and sample sizes. The mouse column contains the mouse model name, the reference containing genetic line information, and then underneath the background strain in italics. Source breeders are indicated in square brackets: J: Jackson, JJ: Janvier, and CR: Charles River. Transgenic: Tg, Non-transgenic: NTg, α-synuclein null: α-syn null, Middle cerebral artery occlusion (Stroke surgery): MCAO, Sham stroke surgery: Sham, Horizontal gaze palsy with progressive scoliosis: HGPPS, female: f, male: m Mouse models were coded for likely sensory, motor or cognitive symptoms, evidence for which is presented more in the discussion.

Mouse	Model system	Symptoms	Sample size and gender	Age	No. clips collected	No. Clips (locomotion)	No. Clips (whisker movements)
SOD1^{G93A} (Mead et al., 2011) *C57BL/6J [J]*	Amyotrophic Lateral Sclerosis	Motor	7 Tg f 8 NTg f	120 days	133	81 Tg 44 NTg	76 Tg 45 NTg
R6/2 CAG250 (Morton et al., 2009) *C57BL/6J x CBA [J]*	Huntington's disease	Motor, Cognitive, Social	8 Tg m 8 Tg f 7 NTg m 8 NTg f	16-20 weeks	522	106 Tg 104 NTg	123 Tg 107 NTg
SNCA-OVX (Janezic et al., 2013) *C57BL/6 [CR]*	Familial and sporadic Parkinson's disease	Motor	9 Tg f 6 α-syn null f	18-19.5 months	150	71 Tg 47 NTg	63 Tg 40 NTg
MCAO 1 month (Kuraoka et al., 2009; Appendix 2) *C57BL/6J [CR]*	Ischemic stroke	Sensory, Motor	12 MCAO m 12 Sham m	1 month post-op Adult	268	129 MCAO 127 Sham	120 MCAO 123 Sham
MCAO 2 weeks (Kuraoka et al., 2009; Appendix 2) *C57BL/6J [CR]*	Ischemic stroke	Sensory, Motor	5 MCAO m 2 Sham m	2 weeks post-op Adult	96	50 MCAO 25 Sham	52 MCAO 23 Sham

Reeler (B6C3Fe) (Falconer, 1951; Guy et al., 2014) *B6C3Fe [J]*	Cerebellar Ataxia, Somatosensory Cortex Development	Sensory, Motor	7 Tg m 6 NTg m	7-9 months	75	84 Tg 72 NTg	56 Tg 61 NTg
RIM-DKO Sert (Narboux-Nême et al., 2012) *129Sv x C57BL/6 [J]*	Somatosensory Cortex Development	Sensory	3 Tg m 2 Tg f 3 NTg m 2 NTg f	6-9 months	59	29 Tg 30 NTg	27 Tg 30 NTg
Robo3R$^{3-5}$-cKO (Renier et al., 2010) *C57BL/6 [JJ]*	Somatosensory Cortex Development, HGPPS	Sensory, Motor	6 Tg m 6 NTg m	1-5 months	228	109 Tg 112 NTg	61 Tg 41 NTg
3xTg-AD (Stover et al., 2015) *B6129SF2 [J]*	Familial Alzheimer's disease	Motor, Cognitive	8 Tg f 6 NTg f	17 months	222	53 Tg 52 NTg	53 Tg 133 NTg
5xFAD (Oakley et al., 2006; O'Leary et al., 2017; 2018b) *C57BL/6J x SJL/J [J]*	Familial Alzheimer's disease	Sensory, Motor, Cognitive	3 Tg f 4 NTg f	12.5 months	80	24 Tg 26 NTg	29 Tg 30 NTg

Experimental Procedures

The procedure for testing was identical in each laboratory, using a custom portable set-up (Grant et al., 2014). Mice were placed in a transparent, Perspex, rectangular arena (20 x 30 x 15 cm), which was lit from below by a bright, infra-red light box (either custom made, or LEDW-BL-400/200-SLLUB-Q-1R-24V, PHLOX) (Figure 1a). Mice were filmed from above using a digital high-speed video camera (Phantom Miro ex2, or Photron Fastcam) recording at 500 frames per second with a shutter-speed of 1 ms (and resolution of 640x480 or 1024x1024 pixels, respectively) (Figure 1a). In most cases, the arena was an open field, with no objects present. However, for models likely to show sensory or cognitive effects (Reeler B6C3Fe, RIM-DKOSert, Robo3R$^{3-5}$-cKO, 3xTg-AD, 5xFAD) an object (either a Perspex cube or small yo-yo) was also placed within the arena to promote exploration. Multiple video clips were collected opportunistically (by manual trigger) when the animal moved into the camera's field of view. Each clip was around one second long. 6-16 clips were collected from each animal over a 5-10 minute period (see Table 1 for the number of clips collected). All clips were selected and trimmed to a portion of footage based on selection criteria developed by Grant et al., (2014). These criteria were: i) the mouse was clearly in frame; ii) both sides of the face were visible; and iii) the head was level with the floor (no extreme pitch or yaw). While data was collected from multiple labs, all videos were analysed and statistics conducted by only one laboratory (at Manchester Metropolitan University), to ensure consistency. Instructions for the experimental procedures, as well as the subsequent video analyses can be found in Appendix 3.

Qualitative Whisker Scores

To assess the general whisker movements and exploratory strategies, clips of just the transgenic and MCAO animals were scored based on a system developed by Grant et al. (2012; 2017, Appendix 3). All the transgenic and MCAO animals were scored for whisking in each included clip. In particular if

the animal was not whisking (0), doing only retractions (1), only protractions (2) or retractions and protractions (3). When an object was present, for Reeler B6C3Fe, RIM-DKOSert, Robo3R$^{3-5}$-cKO, 3xTg-AD, 5xFAD mice, clips where the mouse had contacted the block were also scored for contact-induced asymmetry (CIA) and spread reduction. Contact-induced asymmetry (CIA) was given a score for being absent (0), increased contralateral protraction (1), reduced ipsilateral protraction (2) and both increased contralateral protraction and reduced ipsilateral protraction (3). Spread reduction was scored as absent (0) or present (1), when the whisker spread decreased following a contact. We also scored whether head turning asymmetry (Mitchinson et al., 2011; Towal and Hartmann, 2006) and look-ahead behaviours (Arkley et al., 2014) were present (1) or absent (0); however, these behaviours were not very common and there were no significant differences observed, so they were removed from further analyses.

Quantitative analysis of locomotion and whisker movements

For quantitative analysis of whisker movements and locomotion, clips were further selected, based on two more criteria (developed in Grant et al., 2014): i) the whiskers were not in contact with a vertical wall; and ii) the mouse was clearly moving forward. We wanted to assess here how the whiskers move during forward locomotion without any object contact, as whisker movements are significantly controlled and altered during object exploration. In each included clip, the mouse was tracked using the Automated Rodent Tracker (ART) (Hewitt et al., 2018). This used image analysis to locate the mouse nose tip and centroid, to calculate locomotion speed (from the yellow trace in Figure 1b). A ruler was filmed at the start of each episode of data collection to enable a calibrated measure of locomotion speed in metres per second. The ART whisker detector was validated by manually inspecting the overlaid video footage to check the position of the nose tip and centroid point (Figure 1b). The number of videos included in the locomotion analysis can be seen in Table 1, and was a total of 1397 clips.

The snout and whiskers of the mouse were detected using ARTv2 (the Automated Rodent Tracker, version2), as part of the LocoWhisk software package (Gillespie et al., 2019). This is the first time that this software has been demonstrated on a dataset. The whisker detector automatically found the orientation and position of the snout, and the whisker angles (relative to the midline of the head) of each identified whisker (Figure 1b). ARTv2 is only a whisker detector, therefore, it does not maintain the identity of the whisker between frames (i.e. tracking); rather, in all whiskers that are detected a mean angle is approximated from each frame. Whisker angles refer to the angle that the whiskers made with the mid-line of the nose and head, giving that larger angles represent more forward-positioned whiskers. If whiskers are occluded (such as by whisker crossing) the software will not detect that whisker; therefore, the number of whiskers detected can vary from frame to frame, with a total of 2-12 whiskers detected in each frame (with around 10-12 whiskers being usual, 5-6 on each side). Whisker detection was validated by manually inspecting the software annotations overlaid on to the video frames and a total of 1291 clips, each of around 0.5 seconds in length, were included in the entire analysis. Clips were only included when the mouse was not contacting a wall or object within the arena. The number of videos included in the whisker movement analysis can be seen in Table 1.

Mean whisker angle was calculated by taking a mean of all the detected whiskers on each side, on a frame by frame basis (Figure 1c). The following variables were calculated from the mean whisker angles: mean angular position (the average whisker angle), amplitude (2√2* the standard deviation of whisker angles, to approximate the range of whisker movements), asymmetry (the difference in whisker angles between the left and right sides), and the mean angular retraction and protraction speeds (calculated as the average velocity of all the backward (negative) and forward (positive)

whisker movements, respectively). For mean angular position, amplitude, and whisker speeds, the values for right and left whisker measurements were averaged (mean) to give only one value per clip.

Statistical Considerations

Locomotion was not normally distributed, and therefore, a Mann Whitney U Test was used, with mouse type (transgenic or MCAO vs. controls) as the grouping (between) variable. A significance level of 0.05 was used. The quantitative whisker variables were compared using a MANOVA. The effect of background strain (C57BL/6, 129Sv x C57BL/6, C57BL/6 x SJL/J, C57BL/6 x CBA, B6C3Fe, B6129SF2) and source breeder (Jackson, Janvier (with Jackson mouse) and Charles River) were investigated by grouping whisker variables by background strain and source breeder. As each mouse model was collected from a different lab (apart from the 5xFAD and 3xTg-AD mice, Appendix 1), the effect of lab could not be analysed. Whisker variables were then grouped by mouse genotype (transgenic or MCAO vs. controls) and mouse background (comparing: $SOD1^{G93A}$, R6/2 CAG250, SNCA-OVX, MCAO 1 month, MCAO 2 weeks, Reeler (B6C3Fe), RIM-DKOSert, $Robo3R^{3-5}$-cKO, 3xTg-AD and 5xFAD mice, including all mice: transgenic, MCAO and controls). A Bonferroni correction was applied, so p was significant at values less than 0.01. Individual ANOVAs were conducted to examine the effect of genotype in each mouse model, as each strain and mouse model appeared to be very different. To investigate sex differences, a multivariate ANOVA compared mouse type (transgenic vs controls) as well as sex (male and female) for all the whisker variables. A Bonferroni correction was applied, so p was significant at values less than 0.01. For the qualitative whisker scores, a Kruskal Wallis test was used, with whisking, CIA and spread reduction scores grouped by each mouse model. A significance value of $p<0.05$ was used. Results were plotted as mean bar charts with standard error bars. Significant results are indicated on figures with an asterisk (*).

Results

Quantitative Whisker Scores in control mice: effect of background strain and source breeder

Background strain (MANOVA: $F(25,3495)=22.481$, $p<0.001$) and source breeder (MANOVA: $F(10,1392)=62.342$, $p<0.001$) significantly affected whisker positions and movements in the control mice (Figure 2). This was apparent in all whisker variables measured, including mean angular positions (strain: $F(5,706)=126.688$, $p<0.001$, breeder: $F(2,706)=441.786$, $p<0.001$), amplitude (strain: $F(5,706)=25.323$, $p<0.001$, breeder: $F(2,706)=11.744$, $p<0.001$), retraction speed (strain: $F(5,706)=8.170$, $p<0.001$, breeder: $F(2,706)=64.885$, $p<0.001$), protraction speed (strain: $F(5,706)=14.846$, $p<0.001$, breeder: $F(2,706)= 98.699$, $p<0.001$) and asymmetry (strain: $F(5,706)=6.112$, $p<0.001$, breeder: $F(2,706)= 4.781$, $p=0.009$). Relationships were relatively variable among the background strains, source breeders and whisker variables, with the most variation observed in the mean angular position variable (Figure 2a). For example, the B6C3Fe (Reeler), C57BL/6 x CBA (R6/2 CAG250) and 129Sv x C57BL/6 (RIM-DKO Sert) mice all had significantly different mean angular positions from each other as well as all the other background strains (C57BL/6, C57BL/6 x SJL/J, B6129SF2). Mice from different source breeders also all had significantly different mean angular positions (Figure 2a), protraction speeds (Figure 2d) and retraction speeds (Figure 2e) from one another. For example, the Janvier lab mice (JJ) had the lowest values of mean angular position values, retraction speeds and protraction speeds, compared to the Jackson lab mice (J), which had medium values, and the Charles River mice (CR), which had high values for all. As the majority of mice had a background strain of C57BL/6 (those with white bars in figure 2), just these

mice were then looked at further to see if whisker positions and movements significantly varied in individual models with the same background strain. Indeed, mice with the same background strain had significantly different whisker movements and positions, including mean angular position ($F(2, 332)=48.035$, $p<0.001$), retraction speed ($F(2,332)=33.092$, $p<0.001$), protraction speed ($F(2, 332)=22.324$, $p<0.001$) and asymmetry ($F(2,332)=3.171$, $p=0.043$), but not amplitude ($F(2, 332)=0.858$, $p=0.425$), For example, $SOD1^{G93A}$ mice and MCAO control mice at 1 month of age all had different mean angular position values from each other and all the other mouse models with a C57BL/6 background strain (in white in Figure 2a, including MCAO 2 weeks, SNCA-OVX and $Robo3R^{3-5}$ -cKO mice). This suggests that the host lab might also have an effect on whisker positions and movements. Because background strain, source breeder and lab had such a significant effect on quantitative whisker measurements in the control mice, the transgenic and MCAO mice were compared only to their matched controls, and not within different models (see Quantitative analyses below).

Qualitative Whisker Scores in Transgenic and MCAO mice

The qualitative scores of whisking showed that all the mice fully whisked, apart from R6/2 CAG250 mice ($U(586)=486.3$, $p<0.001$) (Figure 3a), which had significantly reduced whisking scores, compared to the other transgenic mice. The R6/2 CAG250 mice only moved their whiskers forward with protractions, and did not make full retraction movements, giving a score of 2 for their whisker movements. This can also be seen in the example traces in Figure 6b.

In the whisker scores taken during object exploration, the $Robo3R^{3-5}$-cKO mice performed contact-induced asymmetry against the object more often than the other transgenic mouse models, including Reeler B6C3Fe, RIM-DKOSert, 3xTg-AD and 5xFAD mice (Figure 3b) ($U(209)=58.04$, $p<0.001$). Often the asymmetry was also more pronounced in the $Robo3R^{3-5}$-cKO mice, compared to the other mice too; indeed, the example in Figure 4 shows the $Robo3R^{3-5}$-cKO mice (Figure 4 middle) with more pronounced contralateral protractions than the non-transgenic mice (Figure 4 left). The RIM-DKO Sert mice performed spread reduction against an object less often than the other transgenic mouse models, including Reeler B6C3Fe, $Robo3R^{3-5}$-cKO, 3xTg-AD and 5xFAD mice (Figure 3c) ($U(214)=28.34$, $p<0.001$). In fact, visually, the RIM-DKO Sert mice often froze following an object contact and did not move their whiskers for a time. This behaviour was not captured by our measurement and scoring system, but can be seen in Figure 4 (RIM-DKO Sert mice, right), where the whiskers freeze against an object, and show no evidence of spread reduction (compare with Figure 4, control non-transgenic mouse, left).

Quantitative analysis of locomotion and whisker movements

The individual mouse models were variable, with mouse background strain (including transgenic, MCAO and controls) having more of an effect on whisker movements overall (MANOVA: $F(45,6410)=33.155$, $p<0.001$, medium effect size: $\eta^2p=0.189$), than being transgenic (MANOVA: $F(10,255)=1.944$, $p=0.030$, small effect: $\eta^2p=0.008$). An example of which can be seen in Figure 5b, where the $Robo3R^{3-5}$-cKO transgenic and non-transgenic mice both had significantly lower mean angular position values than any other mouse model. Such a large variation in whisker movements between mouse models further justifies comparing only transgenic and MCAO mice with their age-matched controls.

The $SOD1^{G93A}$ mice had significantly slower locomotion speeds than the non-transgenic controls ($U(124)=980$, $p<0.001$) (Figure 5a). However, both the transgenic $Robo3R^{3-5}$-cKO and 5xFAD mice had significantly faster locomotion speeds than their non-transgenic controls ($Robo3R^{3-5}$-cKO:

U(220)=4083, p<0.001, 5xFAD: U(49)=772, p<0.001) (Figure 5a). The R6/2 CAG250, Reeler (B6C3Fe), RIM-DKO Sert and 5xFAD mice all had their whiskers positioned further forward, with significantly higher mean angular positions, than their non-transgenic controls (R6/2 CAG250: F(1,228)=22676, p<0.001, Reeler: F(1,15)=6.904, p=0.010, RIM-DKO Sert: F(1,53)=53.222, p<0.001, 5xFAD: F(1,57)=14.450, p<0.001) (Figure 5b). However, both the MCAO (2 week) and 3xTg-AD mice had their whiskers positioned further back, with significantly lower mean angular positions than their sham and non-transgenic controls (MCAO (2 weeks): F(1,73) = 101.525, p<0.001, 3xTg-AD: F(1,184) = 53.443, p<0.001) (Figure 5b). Examples of whisker traces can be seen in Figure 6.

All the MCAO and transgenic mice had similar whisker amplitudes (Figure 5c) and asymmetry values (Figure 5d) to their sham and non-transgenic controls; apart from the $SOD1^{G93A}$ mice, who had larger amplitude whisks than the non-transgenic mice (F(1,119) = 6.491, 0=0.010), and the MCAO (1 month) mice, which had larger whisker asymmetry than the sham mice (F(1,241)=7.399, p=0.007) (Figure 5c and d). Many transgenic mice had significantly slower whisker speeds than their non-transgenic controls (Figure 5e and f). This included the $SOD1^{G93A}$, R6/2CAG-250 and $Robo3R^{3-5}$-cKO mice for protraction speed ($SOD1^{G93A}$: F(1,119) = 10.826, p<0.001, R6/2CAG-250: F(1,228) = 22.070, P<0.011, $Robo3R^{3-5}$-cKO: F(1,100) = 35.587, p<0.001), and R6/2CAG-250, $Robo3R^{3-5}$-cKO and 3xTg-AD mice for retraction speed (R6/2CAG-250: F(1,228) = 21.306, p<0.001, $Robo3R^{3-5}$-cKO: F(1,100) = 44.613, p<0.001, 3xTg-AD: F(1,184) = 8.875, p=0.005). Examples of whisker traces can be seen in Figure 6.

Sex differences

There were no differences in whisker movements between male and female transgenic and non-transgenic RIM-DKO Sert mice (p>0.01). However, there were significant differences in protraction and retraction speeds, between male and female transgenic and non-transgenic R6/2 CAG250 mice (Protraction speed: F(1,226)=21.069, p<0.001, Retraction speed: F(1,226)=31.681, p<0.001). In particular, the female non-transgenic mice had significantly faster protraction and retraction speeds than the female transgenic and all male mice (Figure 7a and b).

Discussion

Whisking is an ethologically important sensing behaviour that is mediated by a complex set of circuits, involving large parts of the rodent brain (Diamond et al., 2008, Prescott et al., 2011). Thus, whisker movements were significantly affected in many of the mouse models that we tested here, compared to their non-transgenic controls. The Huntington's disease R6/2 CAG250 mice showed the biggest differences in whisker movements that could be seen in both the qualitative scoring and quantitative tracking. The $Robo3R^{3-5}$-cKO and RIM-DKO Sert mice showed differences in exploratory strategies during object exploration, when compared to the Reeler, 3xTg-AD and 5XFAD transgenic mice. Specifically, the $Robo3R^{3-5}$-cKO revealed stronger contact-induced asymmetry than the other transgenic mice, and the RIM-DKO Sert did not show spread reduction. We suggest that making precise measurements of whisker movements is important for capturing motor declines, but qualitatively scoring whisker movements during object exploration is sufficient for capturing some sensory deficits. While taking many different measurements of whisker movements can capture a range of behaviours and motions, measuring mean angular position and whisker speeds will capture most of the differences in background strain, source breeder, genotype and sex.

Motor Disorders

Measuring whisker movements and locomotion in mice with motor deficits has previously been conducted in mouse models of Amyotrophic Lateral Sclerosis ($SOD1^{G93A}$) (Grant et al., 2014) and Huntington's disease (R 6/2, Q175 and HdH knock-in models) (Garland et al., 2018). $SOD1^{G93A}$ mice are a model of Amyotrophic Lateral Sclerosis and have been well- studied using behavioural tests (Bucher et al. 2007); they have splayed hind limbs and impaired gait from around 90 days (Heiman-Patterson et al., 2005). We show here that 120 day-old $SOD1^{G93A}$ mice had significantly slower locomotion speeds, as well as larger mean whisking amplitudes than the non-transgenic mice (Figure 5a and c), in agreement with Grant et al. (2014). However, we also found that $SOD1^{G93A}$ mice had significantly slower protraction speeds than the non-transgenic mice (Figure 5e). Grant et al., (2014) also found slower protraction speeds in $SOD1^{G93A}$ mice, compared to non-transgenic mice, but this was not significant in their data. They also found significantly faster retraction speeds in $SOD1^{G93A}$ mice compared to non-transgenics, which we did not find here (Figure 5f).

The R6/2 mouse model of Huntington's disease exhibit skeletal muscular atrophy and neuromuscular junction abnormalities (Ribchester et al., 2004), with both muscle pathology and motor function decline contributing to motor deficits in these mice (Garland et al. 2018). Motor deficits in these mice can be observed in rotarod tasks, balance beam tests and gait analyses (Carter et al., 1999; Menalled et al., 2003; Morton et al., 2009; Pallier et al., 2009); however, these tasks often lack sufficient sensitivity to characterise disease progression, hence the benefit of measuring a highly quantitative behaviour, such as whisker movements. We found that the R6/2 mice had larger angular positions and slower retraction speeds than the non-transgenic mice (Figure 5b and f and Figure 6a), in agreement with Garland et al., (2018). We found that R6/2 mice also had slower protraction speeds than non-transgenic mice (Figure 5e), which was also found by Garland et al., (2018), but was not significant. They also found a significant reduction in whisker amplitude in R6/2 mice compared to non-transgenic controls, which we did not see in our data (Figure 5c).

One might expect to observe similar results in a Parkinson's disease model, compared to a late-stage Huntington's disease model. However, we did not observe any significant whisker movement or locomotion differences in the SNCA-OVX mice compared to the α-synuclein null controls. However, the R6/2 CAG250 model is a relatively severe model, whereas the SNCA-OVX model is much more subtle. The SNCA-OVX model recapitulates disease-relevant levels of alpha-synuclein and progressively develops motor phenotypes with the onset of rotarod impairment at 18-months. On the other hand, the R6/2 CAG250 mouse model shows considerable motor impairment by 18 weeks as measured by grip strength. Hdh knock-in Huntington's mice are often considered to be a better genetic constrict of Huntington's disease, and have a subtler behavioural phenotype (Jin et al., 2015). Hdh CAG250 knock-in mice also do not have late-stage differences in whisker movements, but reveal early changes in whisker amplitude protraction speeds and retraction speeds as early as 10 weeks old (Garland et al., 2018). Therefore, perhaps testing SNCA-OVX mice at younger ages might reveal more differences in whisker movements. SNCA-OVX mice at 18 months of age have been found to have motor deficits in the rotarod task, and reduced stride length (Janezic et al., 2013), so perhaps an accompanying gait analysis might also usefully compliment this work, such as using the LocoWhisk arena (Grant et al., 2018; Gillespie et al., 2019).

Stroke

The MCAO stroke model has functional motor and sensory impairments, such as deficits in the parallel bar crossing and maze exploration test (Nedermann et al. 2007). While the whisker movements of mice with stroke (MCAO) has not specifically been measured before, some studies

have referred to whisker-use in these animals. The forelimb placing test (Schallert et al., 2000) involves detecting the edge of a table with a forelimb, after touching the edge with the vibrissae. It is thought to be affected following damage to sensorimotor cortex, striatum, spinal cord and related sensorimotor structures, such as in stroke models. The cross-midline test (Woodlee et al., 2005) also explores placement of forelimbs following whisker touch, and MCAO animals do not place their forelimb if the whisker touch is ipsilateral to the limb. Nedelmann et al. (2007) observed that one of their MCAO rats (1-6 days post-surgery) lacked any whisker movements on one side, which would cause whisker asymmetry in our experiment. Indeed, we observed significantly higher values of whisker asymmetry in the MCAO mice 1 month post-surgery, compared to sham controls (Figure 5d). We also observed an increase in mean angular position in MCAO mice 2 weeks post-surgery (Figure 5b, Figure 6c), compared to sham controls. The model used here was the distal MCAO model, which produces only a cortical lesion and is a less severe model of stroke than the proximal MCAO, which induces a cortical and subcortical infarct. It is better for animal welfare but deficits are often hard to detect in this model (Rossell et al., 2013). Therefore, seeing deficits at one month post-lesion is very promising, and whisker analysis may allow this model to be utilized more for studies that require functional outcome measures. The lesion in the model is mainly in sensory cortex (Appendix 2), therefore, the mice are likely to have both sensory and motor deficits. Perhaps MCAO mice will reveal alterations in whisker movements during object exploration, as well as in the open field arena, which should be explored in future work.

Somatosensory cortex development models

As the cortex is likely to play a key role in object exploration and discrimination (Kleinfeld et al., 2006), investigating whisker movements during object exploration is likely to capture the most salient changes in mice with somatosensory developmental alterations. Indeed, we see significant differences in exploratory behaviour in the Robo3R$^{3\text{-}5}$-cKO and RIM-DKO Sert mice compared to other mouse models (Figure 3 and 5). While we demonstrate here that exploratory whisking during contact can be described by a simple scoring system, it is possible to also quantitatively measure behaviours such as whisker spread and whisker asymmetry before and during contact, as per Grant et al. (2009). This might be important in future studies that may wish to examine the extent of exploratory whisker disruption.

The Robo3R$^{3\text{-}5}$-cKO mice have impacted performance on Rotarod tasks and reduced locomotion speeds (Renier et al. 2010). They have disrupted VPM thalamic (barreloid) and cortical (barrel) maps, such that two functional whisker maps exist in these areas, and receive input from both sides of the face (Renier et al., 2017; Gaspar and Renier, 2018). We observed that contact-induced asymmetry was particularly prevalent (Figure 3b) and strongly appeared (Figure 4) in these mice, compared to other transgenic mice. This might be due to abnormal bilateral sensory processing in these animals (Renier et al., 2017). As well as sensory deficits, Robo3R$^{3\text{-}5}$-cKO mice have revealed motor deficits in the rotarod task (Renier et al., 2010); we observed slower protraction and retraction whisker speeds (Figure 5e and f), but faster locomotion speeds in these mice (Figure 5a), compared to non-transgenic controls.

RIM-DKO Sert mice have impaired balance by weaning and can have difficulties maintaining upright postures (Karst et al., 2011). They have a 67% reduction in thalamic projections in to barrel cortex (Narboux-Nême et al., 2012), which is likely to impact sensory processing. We observed that they often froze following a contact, and were not able to reduce their whisker spread, so did not bunch their whiskers on to an object following a contact (Figure 4). We also observed that they had larger mean angular positions (Figure 5b, Figure 6e) than their non-transgenic controls. Reeler mice also have an altered cortex, specifically having disrupted layers in cerebellum and cortex (Falconer, 1951,

Wagener et al., 2016; Guy and Staiger, 2017), but cortical topography often remains intact (Wagener et al., 2016) with lemniscal fibers successfully innervating their target columns (Guy and Staiger, 2017; Wagener et al., 2016). Like the RIM-DKO Sert mice, Reeler mice have impaired balance and difficulties maintaining posture, they can also have tremors from 2 weeks of age (Podhorna and Didriksen, 2004). We did not observe any changes in these mice during object exploration but, like the RIM-DKO Sert mice, we also observed an increase in whisker angular position, compared to their non-transgenic controls (Figure 5b, Figure 6d).

While we have mainly referred to sensory alterations in these mice, cortical areas are also involved in sensorimotor processing through a variety of nested loops (Kleinfeld et al., 2006). Therefore, changes in somatosensory areas are likely to affect both sensing and motion in mice with cortical alterations. Much research in whisker sensing is focussed on the somatosensory cortex, particularly the barrel cortex; however, there remains a major challenge understand the effect of barrel cortex architecture on awake, freely moving, behaving animals (Brecht, 2007). Genetic manipulations of mice have allowed us to alter barrel cortex architecture, especially in terms of incoming axons, neural activity and molecular patterning (Gaspar and Renier, 2018), and we have shown that the whiskers of these mice can be imaged to measure their precise movements and exploration strategies. Measuring whisker movements during object exploration and measuring mean angular position in an open field arena could be applied to many transgenic mouse models, in order to understand more about sensory processing in these animals, and the role of the cortex in whisker touch.

Alzheimer's disease

Measuring whisker movements and locomotion in mice with impacted cognitive functioning has previously been conducted in mouse models of Huntington's Disease (Garland et al., 2018) and Alzheimer's disease (5xFAD) (Grant et al., 2018). Our results show that the 5xFAD female Alzheimer's disease mice at 12.5 months had significantly higher mean angular positions than the non-transgenic mice (Figure 5b), which was also observed in female 7 month-old 5xFAD mice in Grant et al. (2018). The 5xFAD mice have sensory deficits, in both olfaction (Roddick et al., 2014; 2016) and hearing
(O'Leary et al. 2017) tasks. Whisker movement alterations in 5xFAD mice might also be linked to sensory deficits. While we did not observe any differences in whisker movements during object exploration, 5xFAD mice show a reduction of inhibitory interneurons in Layer IV of the whisker barrel cortex, which leads to changes in vibrissae-related behaviour that include a lack of whisker barbering in the home cage and an avoidance of enclosed spaces. These behaviours dissipate when the whiskers are trimmed and Flanigan et al. (2014) suggested that 5xFAD mice might have over-sensitive vibrissae. We do demonstrate that 5xFAD mice have altered whisker angles compared to non-transgenic mice, but are not able to associate this with increased sensitivity of the whiskers.

The 5xFAD mice also have both motor (O'Leary et al. 2018a; 2018b) and cognitive deficits (Roddick et al. 2014; Gür et al. 2019). O'Leary et al. (2018a) found that 5xFAD mice, at 9-10 months of age, showed reduced body weight, reduced rearing in the open-field and impaired performance on the rotarod compared to wild-type controls. At 12-13 months, 5xFAD mice showed reduced locomotor activity on the open-field, and impaired balance on the balance beam. We also show here that the female 5xFAD mice at 12 months of age had slower locomotion speeds in an open-field arena, compared to the non-transgenics (Figure 5a), which supports the finding that they have locomotor impairments from 9 months of age (Bhattacharya et al., 2014; O' Leary et al., 2018a; 2018b). Whisker impairments have been found to be present even earlier in female 5xFAD mice, from 7 months of age (Grant et al., 2018).

The other Alzheimer's disease model (3xTg-AD mice) also have impacted performance on sensory (vision: King et al. 2018; olfaction: Roddick et al. 2016), motor (Stover et al. 2015; Garvock-de Montbrun et al. 2019) and cognitive tasks (Stevens et al. 2015; Gür et al. 2019; Fertan et al. 2019). We found that the 3xTg-AD mice had lower mean angular positions (Figure 5b) and retraction speeds (Figure 5f), compared to their non-transgenic controls. Why angular position would show the opposite pattern, and other variables appear significant in the 3xTg-AD mice compared to the 5xFAD mice is unclear (compare Figure 6g and h). However, it might be due to the differences in disease mechanism and pathologies between the two models (Guzmán et al., 2014). The 3xTg mice do not show the clear age-related motor dysfunction that is observed in the 5xFAD mice, and have even been found to have an enhanced motor phenotype at 6 months of age (Stover et al., 2015; Garvock-de Montbrun et al. 2019). They often perform better than non-transgenic mice on rotarod tasks (Stover et al., 2015; Blanchard et al., 2010; Chen et al., 2013; Garvock-de Montbrun et al. 2019), and have longer stride lengths (Stover et al., 2015). However, we did not observe any significant changes in locomotion, even at 17 months of age, and the 3xTg-AD mice had slower whisker movements overall, compared to non-transgenic mice.

Other effects

We observed a large variation in whisker movements between the mouse models, even in the control mice (Figure 2, Figure 5). This variation had a larger effect on whisker movements than being transgenic (Effect sizes: Mouse background strain: $\eta^2p=0.189$; Genotype: $\eta^2p=0.008$). For example, non-transgenic and transgenic Robo3R$^{3\text{-}5}$-cKO mice had the lowest mean angular positions overall, compared to all other mice (Figure 5b). The highest mean angular position was observed in sham stroke mice, 2 week post-surgery (Figure 5b), which accounts for the significant difference between the sham and MCAO mice. There is no real reason why these control mice have significantly more forward positioned whiskers than any other mice, and care has to be taken that observed differences are from the disorder and not as a result of individual or other differences. Certainly, the effect of background mouse strain and source breeder on whisker movements has not previously been explored. We found that background strain and source breeder both affect whisker movements in control mice. All the mice featured in this study also had different ages, were from different labs, and had different sample sizes in each group (due to availability), so we are not able to systematically compare them (Table 1). It is likely that husbandry procedures and enrichment will have an effect on whisker movements, as the development of whisker movements are likely to be experience-dependent (Grant et al., 2012); individual husbandry details for the mice can be found in Appendix 1. Age is also likely to have an effect, due to age-related and experience-dependent effects (Grant et al., 2012). Collecting samples from many mice in different labs will help us to understand the variation of whisker movements, as well as ensuring that videos and set-ups are comparable between each experiment. It is likely that holding and husbandry conditions, background strain, source breeder, age and sex will all impact whisker movements and exploratory behaviours.

Indeed, we also observed an effect of gender in the R6/2 CAG250 mice, specifically that the non-transgenic females had faster protraction and retraction speeds than the non-transgenic males, and transgenic males and females (Figure 7). RIM-DKO Sert mice did not reveal any significant differences between males and females. No studies have systematically explored sex differences in whisker movement in different strains of mice or rats, however, Grant et al. (2018) found that 5xFAD Alzheimer's disease mice revealed significant sex differences, with female mice moving their whiskers much more than the males overall. Of course, there are many sex differences in mouse models, in general (Jonasson, 2005; Schellinck et al., 2010; Roddick et al., 2014; 2016; Kane et al. 2018; Gür et al., 2019), and often females are affected more by disease pathologies (Bhattacharya et

al., 2014). A systematic exploration of sex differences in healthy mouse strains needs to be conducted before whisker measurements become a standard behavioural test.

Other outcomes can also arise as part of breeding mice. For example, some 5xFAD and wildtype mice have retinal degeneration and are completely blind (Chang et al., 2002; Dalk and Graw, 2005) as a result of the retinal degeneration gene (Pde6brd1) in the SJL/J background strain, (Chang et al., 2002). C57Bl6N mice also show some retinal degeneration (Mattapallil et al., 2012). Rats and mice with retinal degeneration have been shown to move their whiskers more than sighted animals (Arkley et al., 2014; Grant et al., 2018), and Grant et al. (2018) showed that sex differences and retinal degeneration both affected whisker movements more than being 5xFAD transgenic. Indeed, measuring whisker movements is so precise, that we are able to pick up many differences in movements, and we can observe differences in mice with certain backgrounds and genotypes. This might mean that a mouse with the same transgene might produce a different behavioural phenotype if they have a different background strain, as background strain affects whisker movements. It is important to understand any behavioural variation that may arise in mouse models, and multi-lab studies such as this is good place to start describing behavioural variations.

Recommendations

That our results are mainly in agreement with other studies (Grant et al., 2014; Garland et al., 2018; Nedelmann et al., 2007) indicates that measuring whisker movements are a robust and repeatable way to capture motor deficits. Indeed, it is highly quantitative and also quick to capture videos, taking only 5-10 minutes per mouse. Measuring whisker movements can also reveal earlier motor deficits than in locomotion tasks, which has already been demonstrated in R6/2 CAG250, HdH CAG250 knock-in and 5xFAD mice (Garland et al., 2018; Grant et al., 2018). However, so far, whisker movement data has been collected by only one laboratory; more laboratories would have to conduct data collection in order to truly test the robustness of using whisker measurements to characterise sensory, motor and cognitive disorders. Collecting more whisker movement data from mouse models of other disorders in open field experiments would also usefully complement this dataset.

As whisker movements are very fast and the whiskers themselves are very small, it is important to review the video footage and make sure that findings from the whisker traces are robust and evidenced clearly by the videos. We suggest that qualitative scoring should be carried out before undertaking tracking on the videos. This can clearly identify large changes in whisker movements (such as in the R6/2 CAG250 mice in Figure 3a and Figure 6b) and also demonstrate whether contact-related measures need to be extracted (such as comparing spread or asymmetry before and during contact, as detailed in Grant et al. (2009)). As in most behaviour studies, significant effects should also be accompanied by example video stills or whisker traces that further demonstrate the effect. Indeed, the experimenter needs to ensure that significant effects are truly caused by being transgenic and not by gender or individual differences (such as in the sham stroke mice in Figure 5b). We suggest that open field arenas are suitable for measuring the whisker movements of mice with motor disorders, but filming whisker movements during object exploration is a useful addition for other mouse models that have sensory, exploratory or cognitive deficits. We also suggest that, where possible, both genders should be considered to incorporate sex differences. Accordingly, we suggest for future studies testing whisker movements in mouse, or even rat, models to follow the methods schematic in Figure 8 (see also Appendix 3 for more details on testing and tracking).

Overall, we demonstrate here that, with a number of caveats, measuring whisker movements can provide precise, quantitative descriptions of motor and exploratory behaviour in many mouse

models. The variety of mouse models available can capture a range of diseases and disorders, as well as provide careful manipulations of brain structure and circuitry. Measuring whisker movements in mouse models could help us to better understand disease progression and design new treatments. It also has the capacity to provide us with a more in-depth understanding of sensory processing.

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FIGURES

Figure 1: Experimental data collection and video analysis. a) filming set-up, showing the Perspex box and high-speed video camera. The yellow box indicates the field of view, and corresponds to b) which shows an example video clip of a mouse. ARTv2 LocoWhisk software automatically locates the mouse centroid (red point, yellow line), nose tip (Red point, blue line) and whiskers (coloured lines). c) The coloured lines of the whiskers make an angle with the head, termed whisker angle. The mean whisker angles of each side are shown here for the left (blue) and right (red) whiskers.

Figure 2: Summary of the quantitative whisker movement data for control mice to examine background strains, for a) mean angular position, b) amplitude, c) asymmetry, d) protraction speed and e) retraction speed. Bars show mean values with standard error bars. Colours and patterns on the bars correspond to the background strain (see key on figure), with white bars corresponding to a C575L/6 background strain, and grey and black bars corresponding to various C575L/6 crosses. Letters above the bars correspond to source breeders: J: Jackson, JJ: Janvier, and CR: Charles River.

Figure 3: Qualitative whisker movement scores. Whisker movement scores for whisking (a), contact-induced asymmetry (CIA) (b) and spread reduction (c). Bars show mean values with standard error bars. Asterisks show significant values ($P<0.05$) for the transgenic or MCAO mice, compared to each other.

Figure 4: Example video stills of mice exploring a Perspex block, pre-contact (top) and during contact (bottom). Control mice (left) show contact-induced asymmetry on the block, and also spread reduction. Robo3R$^{3\text{-}3}$-CKO mice (middle) show many strong instances of contact-induced asymmetry during contact. RIM-DKO Sert mice (right) do not show spread reduction on the block during contact.

Figure 5: Summary of the quantitative locomotion and whisker movement data for transgenic or MCAO mice (in black) and control mice (in white). For locomotion speed (a), mean angular position (b), amplitude (c), asymmetry (d), protraction speed (e) and retraction speed (f). Bars show mean values with standard error bars. Asterisks show significant values ($P<0.01$) for the transgenic or MCAO mice compared to the control mice.

Figure 6: Examples of whisker angle values, illustrating differences in whisker movement traces between transgenic or MCAO mice (solid black line) and control mice (dashed black line).

Figure 7: Sex differences in the R6/2 CAG250 mice. Female non-transgenic control mice had larger protraction (a) and retraction (b) speeds than any of the other mice. Black bars are transgenic and white bars are non-transgenic controls. Bars show mean values with standard error bars. Asterisks show significant values ($P<0.01$)

Figure 8: Suggested future methods schematic for testing mouse models with likely motor (blue), sensory (purple) or cognitive (red) symptoms.

Figure 1

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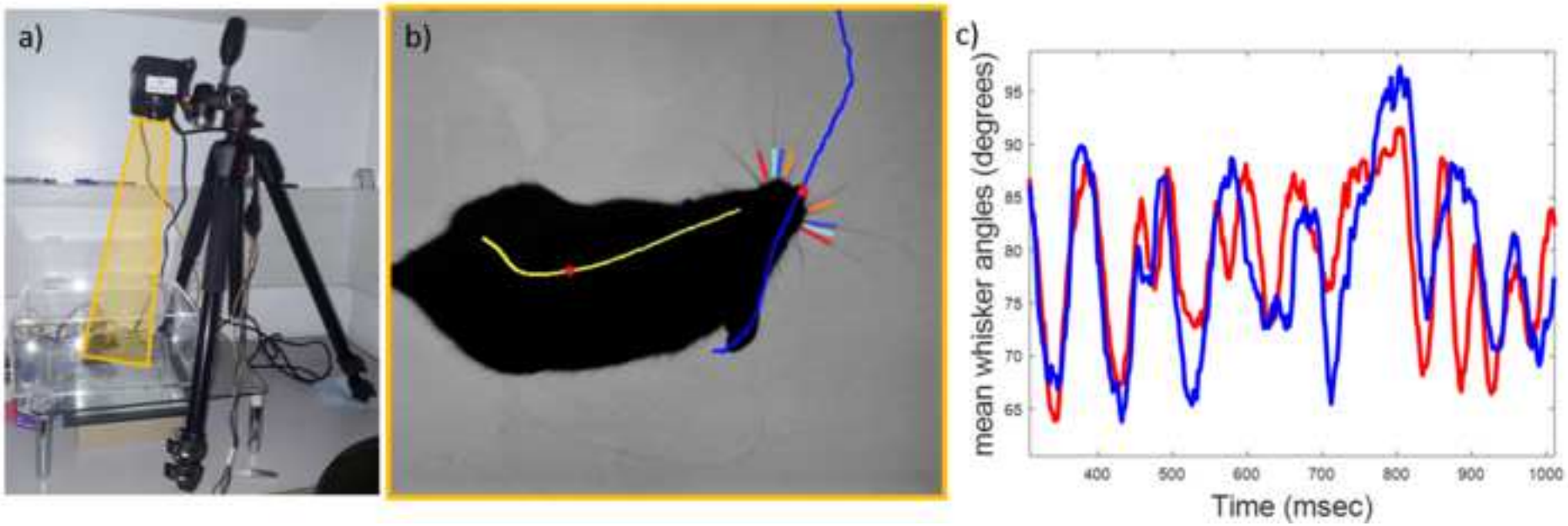

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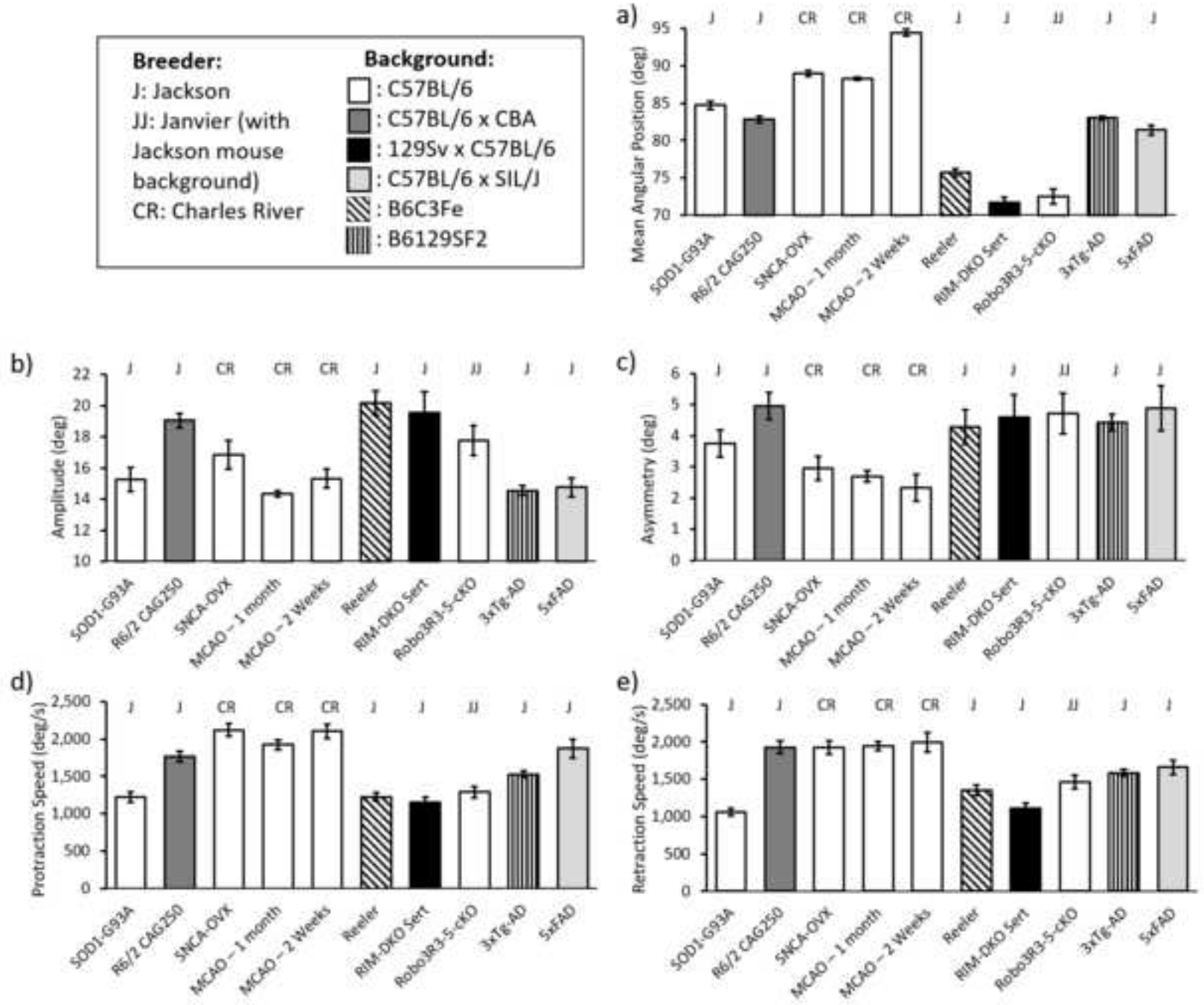

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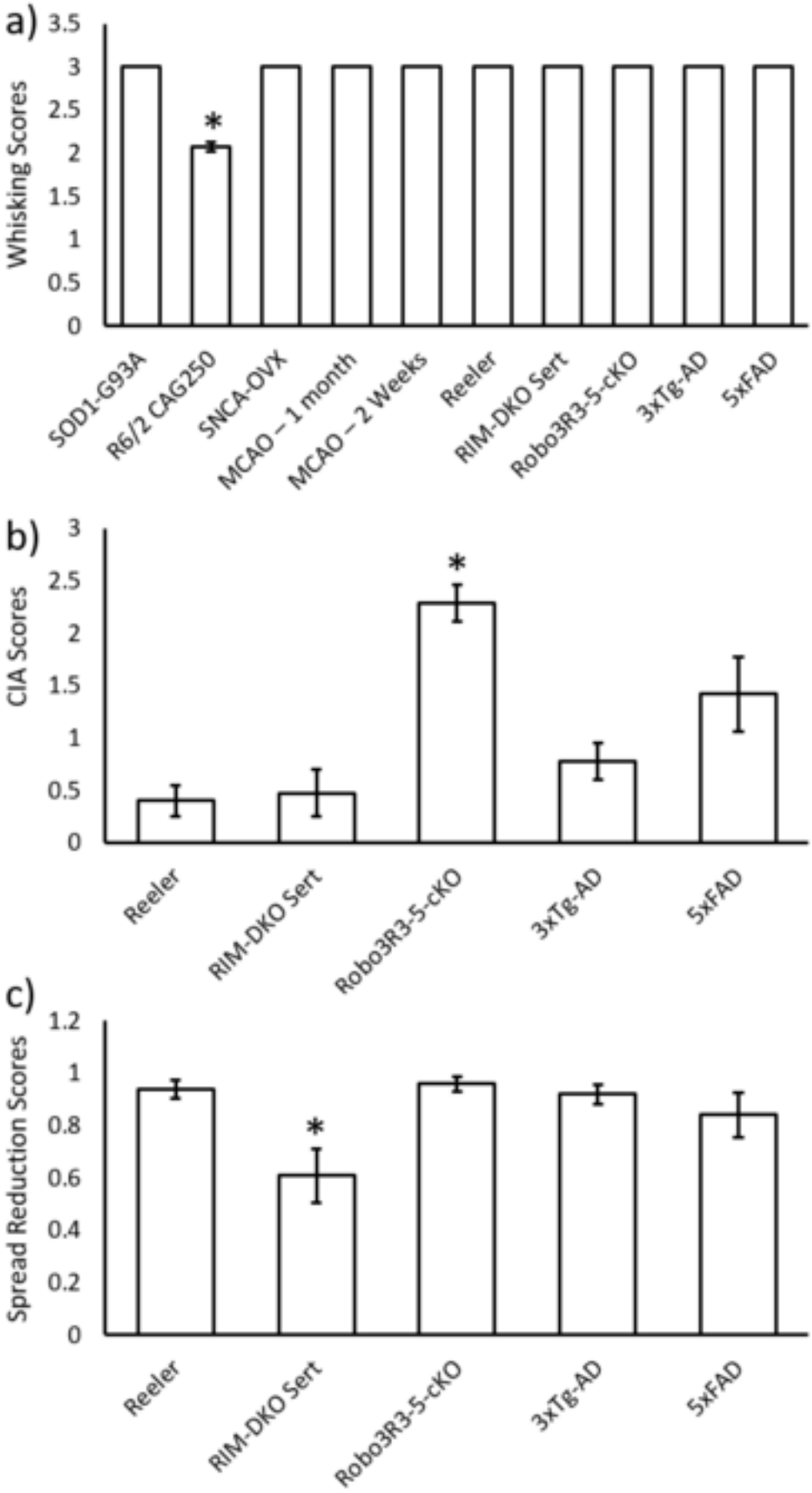

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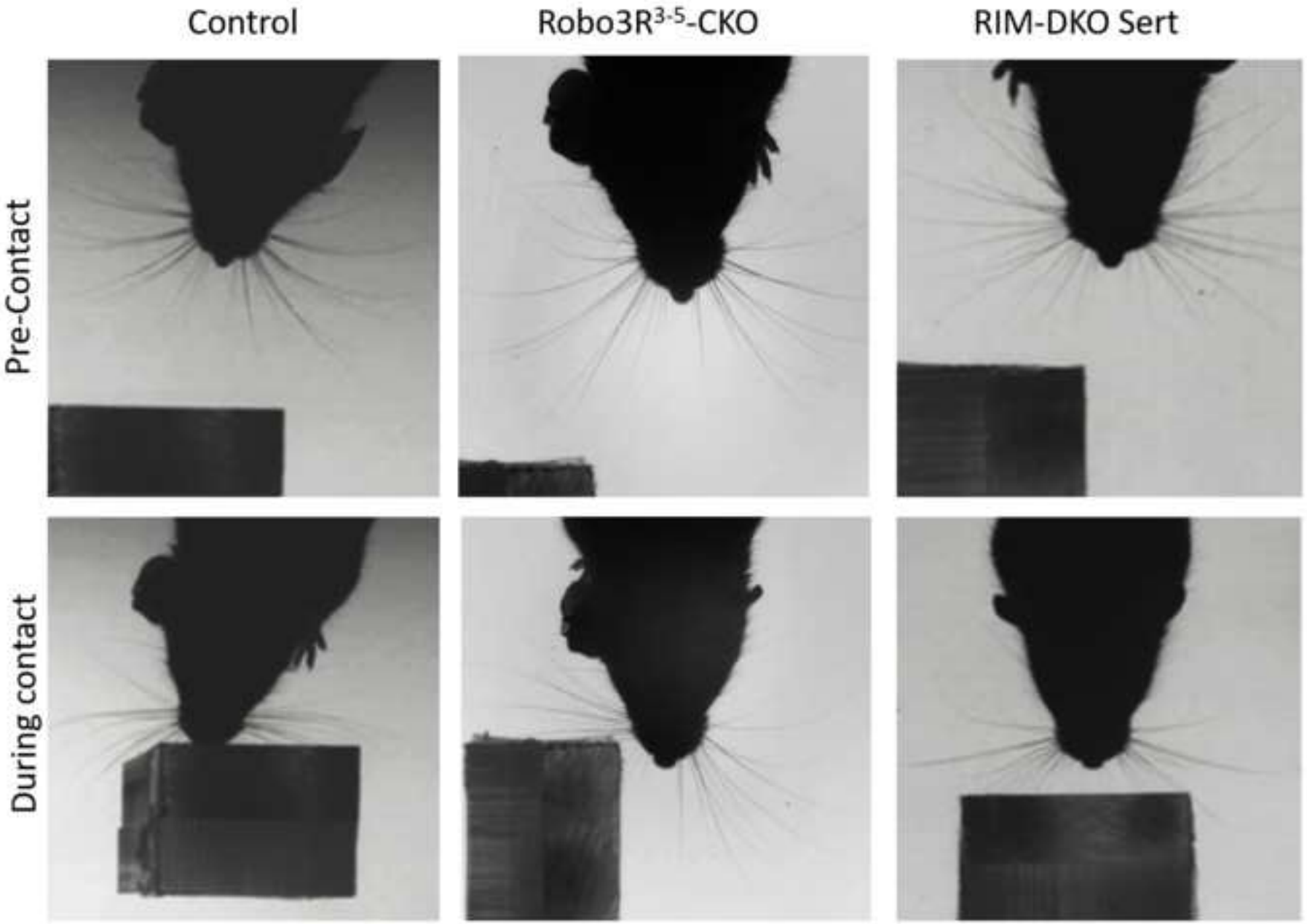

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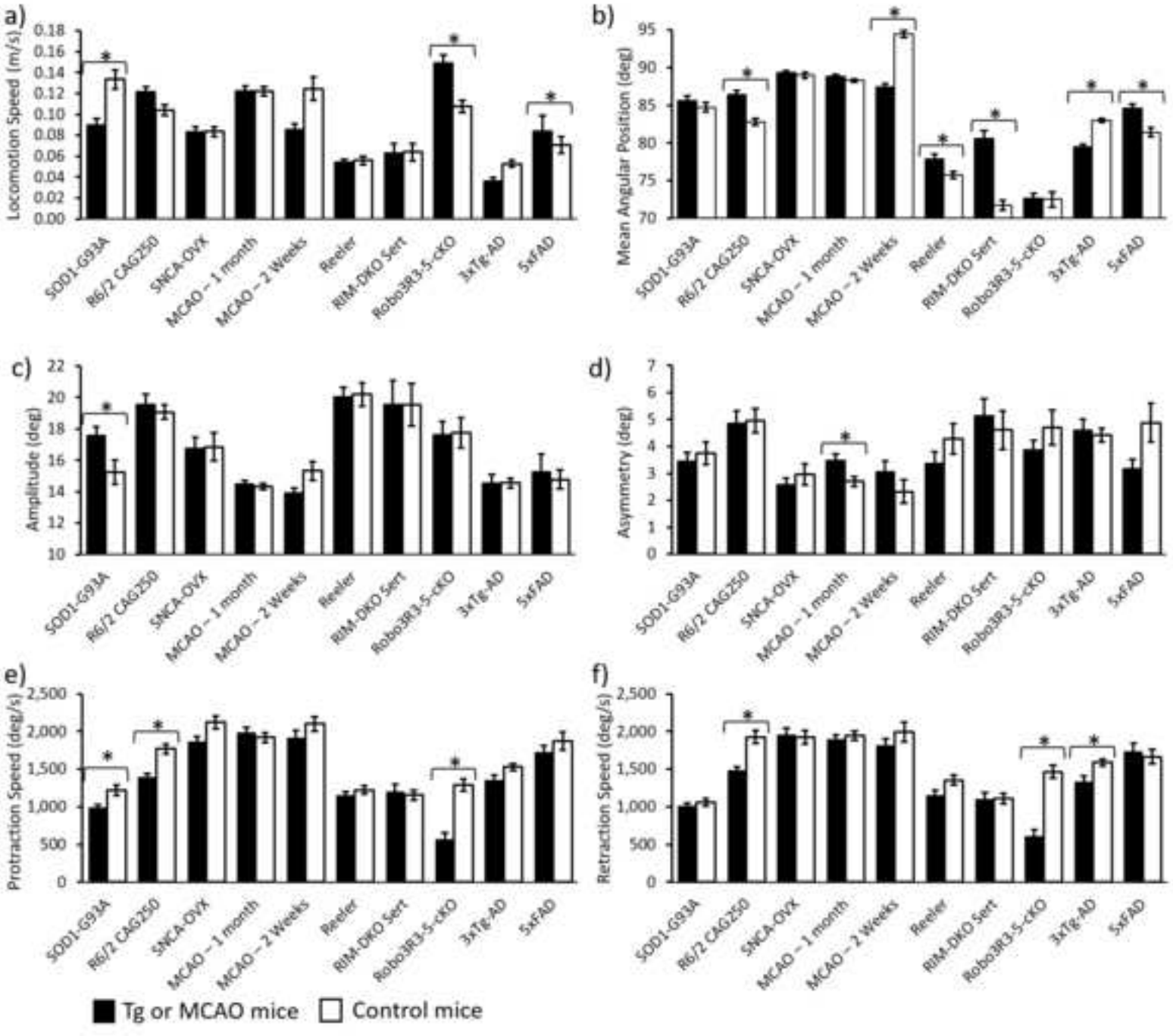

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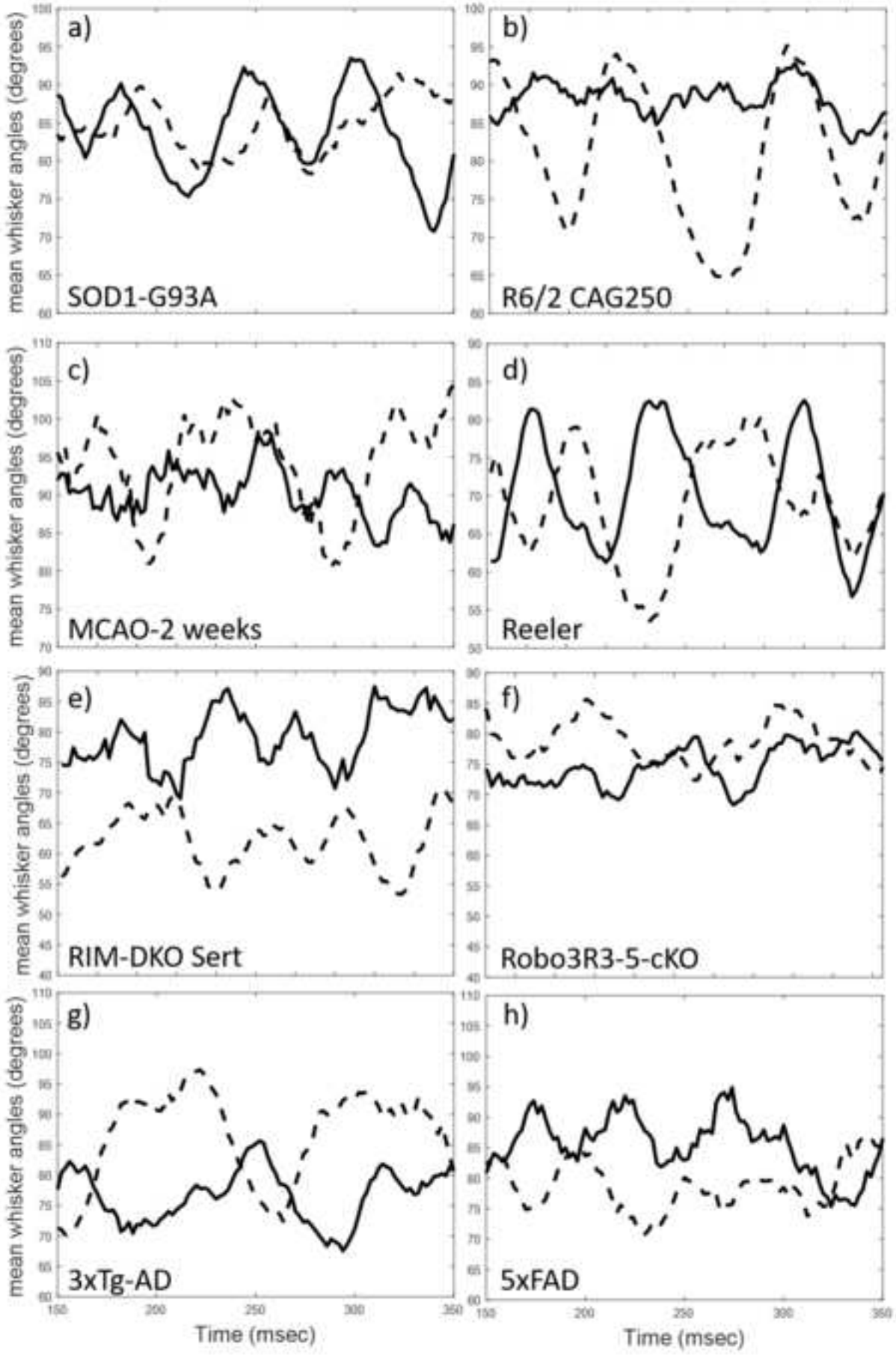

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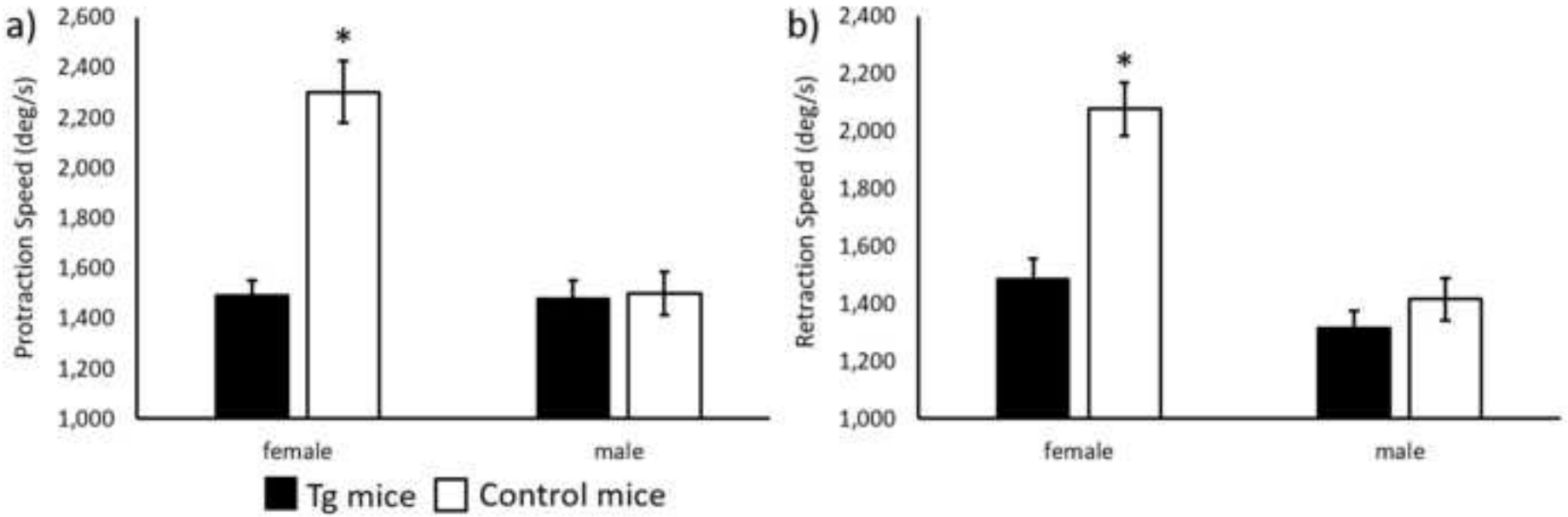

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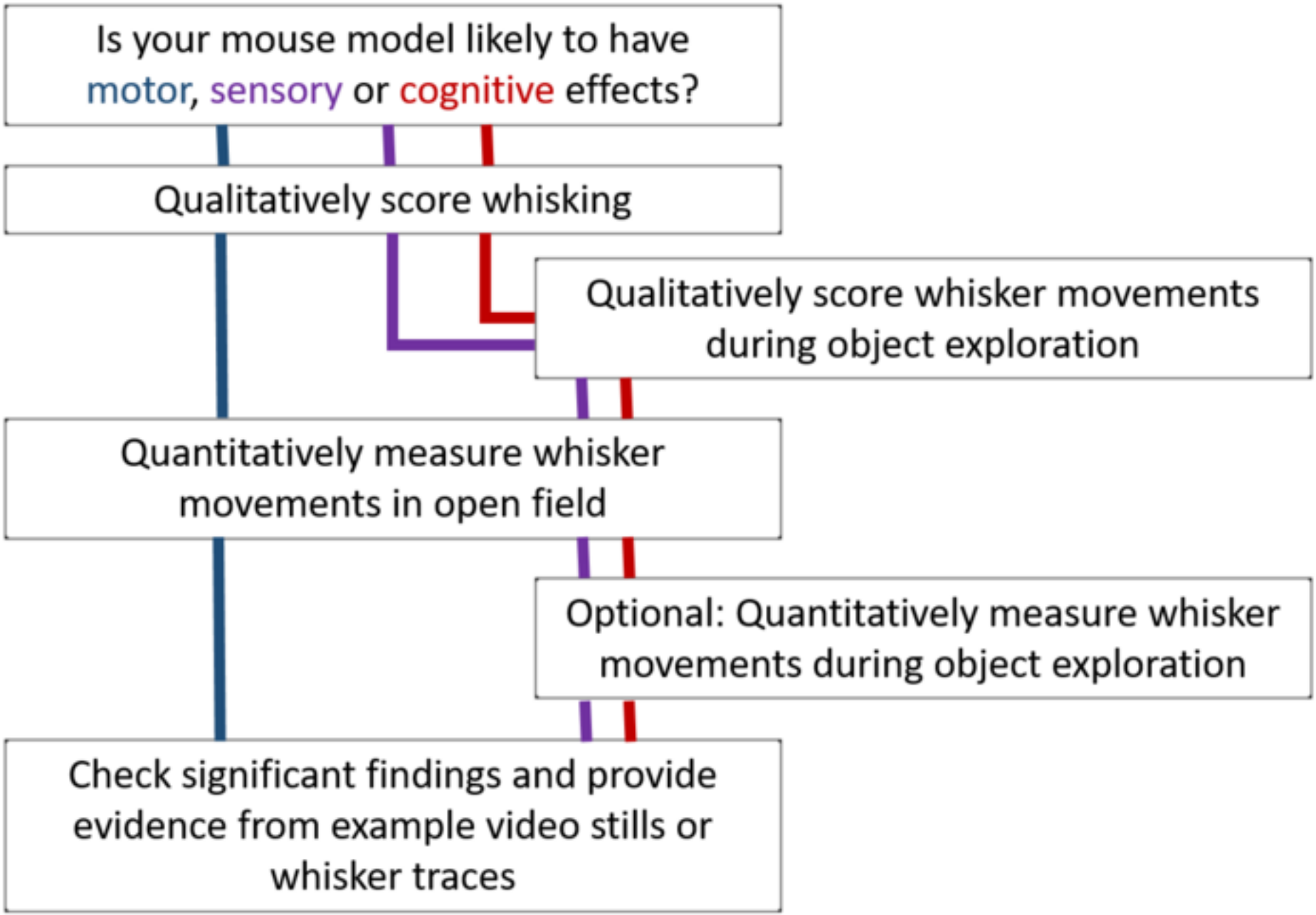

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